SpiderClip: Towards an Open Source System for Wearable Device Simulation in Virtual Reality

Dirk Queck
Technische Universität Kaiserslautern
Serious Games Engineering
Kaiserslautern, Germany
queck@eit.uni-kl.de

Iannis Albert*
Technische Universität Kaiserslautern
Serious Games Engineering
Kaiserslautern, Germany
albert@eit.uni-kl.de

Philipp Zimmer
Technische Universität Kaiserslautern
Serious Games Engineering
Kaiserslautern, Germany
phzimmer@rhrk.uni-kl.de

Nicole Burkard
Technische Universität Kaiserslautern
Serious Games Engineering
Kaiserslautern, Germany
burkard@eit.uni-kl.de

Georg Volkmar
University of Bremen
Digital Media Lab
Bremen, Germany
gvolkmar@uni-bremen.de

Bastian Dänekas
University of Bremen
Digital Media Lab
Bremen, Germany
daenekba@uni-bremen.de

Rainer Malaka
University of Bremen
Digital Media Lab
Bremen, Germany
malaka@tzi.de

Marc Herrlich†
Technische Universität Kaiserslautern
Serious Games Engineering
Kaiserslautern, Germany
herrlich@eit.uni-kl.de

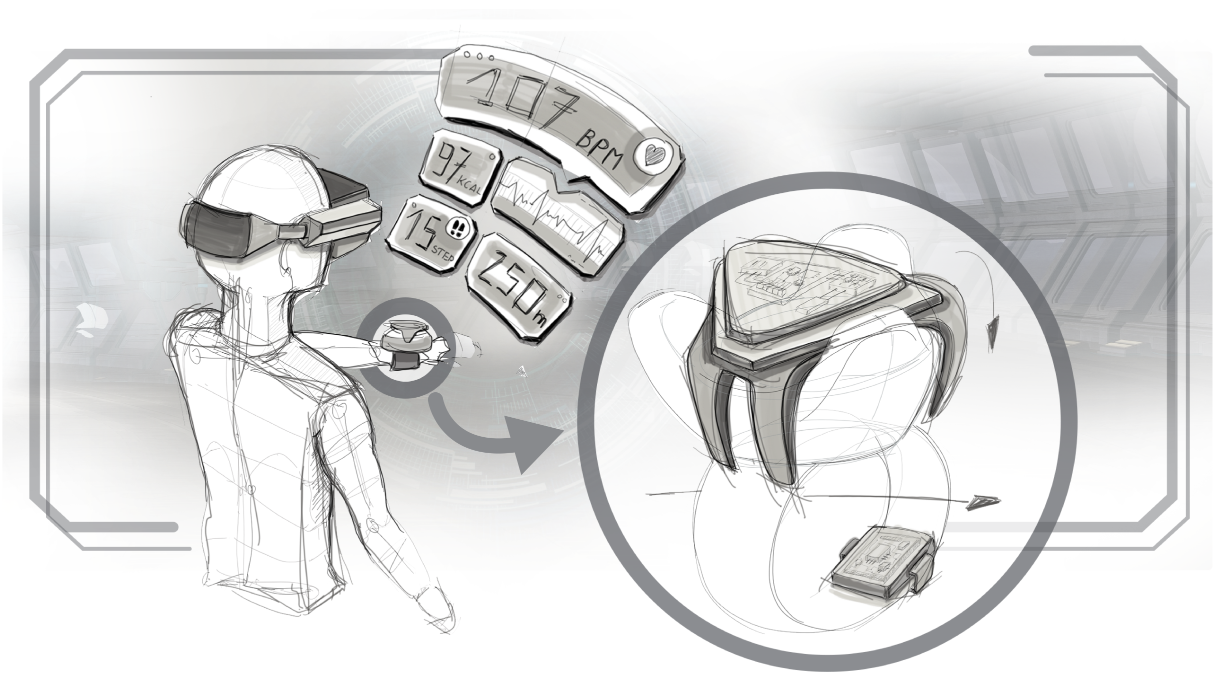


Figure 1: SpiderClip enables access to sensor data and offers a user interface for the simulated wearable in VR.

*Also with University of Bremen, Digital Media Lab.
†Also with German Research Center for Artificial Intelligence (DFKI), Interactive Machine Learning.

CHI '22 Extended Abstracts, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9156-6/22/04…$15.00
https://doi.org/10.1145/3491101.3519758

ABSTRACT

Smartwatches and fitness trackers integrate different sensors from inertial measurement units to heart rate sensors in a very compact and affordable form factor. This makes them interesting and relevant research tools. One potential application domain is virtual reality, e.g., for health related applications such as exergames or simulation approaches. However, commercial devices complicate and limit the collection of raw and real-time data, suffer from privacy issues and are not tailored to using them with VR tracking systems. We address these issues with an open source design to facilitate the construction of VR-enabled wearables for conducting scientific experiments. Our work is motivated by research in mixed realities in pervasive computing environments. We introduce our system and present a proof-of-concept study with 17 participants. Our results show that the wearable reliably measures high-quality data comparable to commercially available fitness trackers and that it does not impede movements or interfere with VR tracking.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**; **Ubiquitous and mobile computing systems and tools**; **Ubiquitous and mobile computing design and evaluation methods**; **Mobile devices**.

KEYWORDS

open science, virtual reality, wearable, sensors, open source, 3d printing, user interface

ACM Reference Format:
Dirk Queck, Iannis Albert, Philipp Zimmer, Nicole Burkard, Georg Volkmar, Bastian Dänekas, Rainer Malaka, and Marc Herrlich. 2022. SpiderClip: Towards an Open Source System for Wearable Device Simulation in Virtual Reality. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '22 Extended Abstracts), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3491101.3519758

1 INTRODUCTION

Over the past years, wearables have become commonplace and for many people have replaced the simple watch in their everyday life. While they started out as digital sports and well-being devices in the form of simple step counters and wearable heart rate monitors, they are increasingly used as general activity trackers worn by many people. Their inconspicuousness and the multitude of integrated sensors also make them ideal tools for research in various application areas such as sports [2], health [5], or even for designing cross-device interaction [22]. But these wearables cannot only be used as daily companions, wearable technology can also be used as a virtual companion like the *YUR.watch* [1] or as an interaction device for VR [6, 17, 19]. VR wearables could be used to enhance training and education programs, such as for first responders [23], pilots [16] or firefighters [4]. With the ability to monitor, log and use data, situations can be assessed, reflected upon and improved, or adjustments can be made dynamically in the application [7]. However, the integration of wearable devices in VR is not trivial. There is currently no specific setup to explore the interaction of wearables in VR. This circumstance requires open tools and platforms to provide access to raw data sources and additionally the possibility of tracking. But the openness, extensibility, and reproducibility of commercial systems is limited and not focused on VR. In addition, the registration processes of many devices are cumbersome and often do not provide full data access.

Feedback about personal physiological data can have a large impact on progress and enjoyment in gaming and virtual training contexts. However, the measurement and transfer of this data from fitness tracker to VR application is usually quite complex. Typically, smartphones have to be used as middleware to access data from the tracker. In addition, such setups often require various platform specific accounts and libraries, some of which might even require regular online validation or exposing personal data to device or software vendors. Therefore, our goal is to develop a tool that works as a wearable in VR and that allows us to directly start and control the collection of user data to better understand the use of wearables in virtual space and to study the impact of different physiological data in VR.

To address these challenges, we developed SpiderClip, an open modular system that integrates common sensors and functionalities from smartwatches but within an open and extendable hardware and software framework. We are working on a framework that allows access to all sensor data in VR and allows direct monitoring and data collection by the user. By doing so, we want to facilitate research that provides better understanding of how wearables can be used in virtual or mixed reality and how users interact with the information of the body measurement data.

We have taken first promising steps and conducted a proof-of-concept study with 17 participants. Our results show that SpiderClip can measure data with accuracy comparable to off-the-shelf devices while being used in VR and that it does neither impede users' movements nor interfere with VR tracking.

2 RELATED WORK

Wearable Design Space (for Virtual Reality). In their work Jarusriboonchai and Häkkilä outline the design space of wearable technology and identify four customization attributes: function, interaction technique, location on the body, and appearance [8]. While the principal design space is huge and is increasingly being explored by the research community, today's commercial smartwatches and fitness trackers focus mostly on watch-like devices worn on the wrist. Considering VR or mixed reality, wearables themselves are subject to Milgram's Reality-Virtuality Continuum [14] and *degree of virtuality* needs to be added to Jarusriboonchai and Häkkilä's list of attributes in this context. The *degree of virtuality* defines which components of the wearable can or should be virtual or simulated and which should or have to be physical for design or technical reasons.

Sensor Platforms and Tools. While the currently dominating commercial platforms from vendors such as Google, Apple, Samsung or Fitbit can be employed within research projects, usage is typically limited to the processed data they provide "as-is". Especially with respect to raw and real-time data commercial devices are constrained, vendors require the creation of platform specific accounts

[1]YUR.watch, https://yur.fit/watch, visited 09.09.2021

and devices are optimized to work with mobile OS platforms such as Android or iOS. There exist a number of more or less open platforms and tools to address these problems, however, they are not specifically addressing the requirements of mixed or virtual reality research. The utility of wearables with respect to data collection is defined by the type and capabilities of the integrated sensors. In most fitness trackers and smartwatches, inertial measurement units (IMUs) provide the foundation for various activity recognition and measurement algorithms. Many devices also feature optical heart rate and blood oxygen sensors. For example, the sensor development platform *Movesense* [2] integrates an IMU and heart rate sensor. Data can be recorded locally by the device and accessed using a smartphone app. Application examples include fall risk detection [20]. Due to its compact size (36.6mm x 36.6mm x 10.6mm) and available developer tools and accessories, the sensor platform principally satisfies many technical requirements but it is designed as a general solution and not intended for use as VR wearable. The system lacks the possibility of adaptation to VR tracking systems or controllers and direct integration into VR projects. In addition, the system is designed for use with smartphones and from a mid-term to long-term research perspective there is still the danger of vendor lock-in or discontinuation of the platform as a whole. Existing tools and devices from *BITalino* [3] or the *Open Source Health Activity Kit* [4] *(openHAK)* offer a wide range of possibilities for the acquisition of body measurement data but are also not designed as MR wearables. In addition, openHAK uses a number of very specific components to achieve a form factor comparable to commercial devices, which are not sold anymore and are not trivial to replace for non-experts. The design goal of openHAK is to provide an open source "real world" fitness tracker but not a flexible research platform for VR.

Wearables in Virtual Reality. Several works explore the intersection of wearables and VR. Hirzle et al. investigate novel smartwatch interaction methods by comparing touchscreen inputs with input derived from inertial sensors [6]. In addition, they compare the influence of the location of the wearable (handheld vs. wrist-worn). They calculate gestures from motion data based on a technique proposed by Pietroszek et al. This technique allows target selection and shifting by assigning the Z coordinate position to the forearm rotation [18]. While both works achieve interesting results using existing devices, Hirzle et al., for instance, note that the position of the smartwatch was not traceable and they had to fall back to using the user's head as a reference point for certain calculations [6]. This examples emphasizes the potential of a reliable and easy to use integration of VR tracking with wearable sensor devices.

Similar work is presented by Rupprecht et al., who investigate interaction techniques for smartwatches and mobile HMDs as well [19]. They examine seven different gestures to interact in a virtual environment and compare them to common VR input technology (body tracking using a 3D camera). They investigate a 3D camera setup against using IMU data from a smartwatch for gesture input and find that smartwatch interaction provides equally good or better results than 3D camera-based input for most gestures in their experiment.

Stellmacher et al. investigate the design space of using sensor data collected by smartwatches in VR [24]. They explore menu navigation using smartwatch motion data, touch-based gestures and dynamic adaptation of the virtual environment based on health data. They use the Fitbit Versa fitness tracker and an Android-based smartphone. In line with our previous argument, they note that smartwatches typically provide web-based APIs and that this entails limitations in scenarios requiring real-time data such as low-latency gesture recognition.

Meier et al.'s TapID is a notable approach letting users interact with physical objects in VR through free hand movements [13]. Touch recognition is based on IMU data and integrated with hand tracking information provided by the VR headset. This approach could possibly be utilized to simulate wearable touch-displays using simple physical objects as tactile proxies. A future direction of investigation might be a combination of SpiderClip and the touch recognition approach of Meier et al.

Physiological data provided by wearables can be used in VR applications like exergames to enhance the (game) user experience as shown in previous work, e.g. for exercise intensity control [21], incentive systems for increased exertion [10], balancing of different fitness levels in multiplayer exergames [1] or using visualizations of live data for the sake of coaching the players [11]. Moreover, live data could be used to enhance exertion-based procedural level generation in exergames [12, 27] to not only generate a level based on the prospected exercise intensity from the start but to react to the physiological data of the players to adapt and customize the level on the fly.

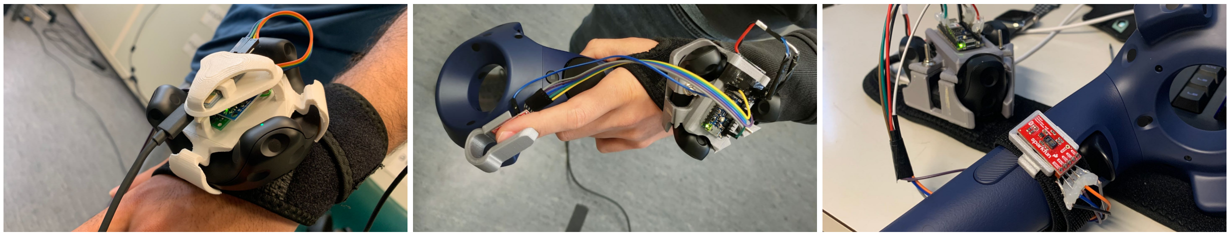
The works we found in the literature as discussed above successfully employed commercial devices. However, these works also show that the technical complexity of getting these devices to work within the context of research is very high. It typically involves a combination of smartwatches or fitness trackers with smartphones and VR devices and developing custom apps with a good knowledge of vendor specific and smartphone specific APIs and development tools. This significantly raises the entry barrier to conducting experiments specifically in an interdisciplinary community. On the other hand, these works illustrate the potential of wearables in VR and the relevance of our approach.

3 REQUIREMENTS

General Requirements. The development of SpiderClip is guided by a number of principal requirements.

(1) The "openness" of the system is an important principle as discussed in the introduction. Therefore, the system should be able to provide direct and easy access to all processed and raw data.
(2) As real-time access to data is one major limitation of other frameworks and devices, SpiderClip should ensure that data transfer is fast and with minimal delays.
(3) The device should not disturb the users or the VR tracking. Therefore, it should be as lightweight as possible and work without cables. In terms of general ergonomics and usability, using the device should not restrict or strain the user

[2] Open Wearable Tech Platform (movesense), https://www.movesense.com/, visited 10.01.2021
[3] all-in-one toolkit for biosignals acquisition (BITalino), https://bitalino.com/products/board-kit-bt, visited 05.01.2021
[4] Open Health Activity Kit (openHAK), https://www.openhak.com/, visited 09.09.2021



(a) SpiderClip (version 1) attached to a Vive Tracker using a clipping system **(b) The heart rate sensor is attached to the index finger with a finger clip** **(c) Attachment of the heart rate sensor directly to the controller**

Figure 2: Different ways of attaching SpiderClip to different tracking systems

and usage should require little to no learning. Housing and electronic components must not interfere with VR tracking.

Sensor Requirements. In addition to the general guiding principles as listed above, we reviewed the most popular currently available off-the-shelf wearable devices to derive a set of technical requirements with respect to included sensors and recognition features.

For this, we analyzed the devices with regard to the following criteria:

(1) What sensors does the wearable have?
(2) What parameters does the wearable track?
(3) How does the device communicate with the smartphone or computer?

We determined the minimum system requirements by using a ranking method with respect to the criterion frequency [28]. We selected all sensors and parameters that could be found in 15 wearables (from well-known manufacturers such as Xiaomi, Garmin, Fitbit, Samsung, Apple, Huawei and Amazfit) which corresponded to a frequency of 80 % and was sufficient for our heuristic approach. This means that the wearable should have at least a 3-axis accelerometer, 3-axis gyroscope and a way to measure heart rate. The system must be able to measure parameters such as steps, heart rate and calories. In addition, time and date display as well as direct connection to the application are necessary.

4 SPIDERCLIP SYSTEM

The SpiderClip system consists of two parts: a hardware part that can be attached to a compatible VR tracker (currently we support HTC VIVE tracker 1.0, 2.0 and 3.0) via clip or screw mechanism and a Unity Game Engine asset that manages the data connection via serial port and can render a virtual watch that displays the sensor data measured by the hardware components.

SpiderClip Hardware Components. The hardware components of SpiderClip consist of a Vive tracker, a 3D printed housing, and a sensor platform based on the Arduino framework. For the sensor platform, we work with open source solutions to make the system as future-proof as possible, easy to replicate for other researchers and to facilitate changes and extension. The platform contains an *Arduino Nano Every* [5], a *Sparkfun Pulse Oximeter and Heart Rate Sensor* [6] and a *HC-05 Bluetooth Module* [7]. We used several libraries based on the available sensors and a modular software design that provides all sensor data packages for the virtual watch. We experimented with different sensors and components to achieve a good balance with respect to the requirements. The source code for the microcontroller can be downloaded from *Github* as *SpiderClip Sensor* [8] project. The system is intentionally kept open and can be extended or modified by adding new sensors or replacing components. We went through several internal iterations with different locations and attachment solutions for the heart rate sensor (cf. Figure 2b) and the device itself, such as attaching it to the VR controllers (Figure 2c), and trackers (Figure 2a) to compare the respective ergonomics and data quality. We tested tracking with multiple generations of the Vive tracker (Figure 2a and Figure 2b). We also experimented with the 3D printed design to improve the tracking and handling of the Vive tracker and test different ways to house the battery to balance between power supply and weight. The goal was to be able to use the system for several hours without creating an uncomfortable wearable for the user. The latest version of SpiderClip weighs 38 g (without the tracker) and the battery lasts for approximately four hours and 20 minutes.

SpiderClip Virtual Watch. Another important part of the system is the virtual watch interface. SpiderClip provides various sensor data that can be retrieved by an application. It can measure linear and rotational acceleration data from which various parameters can be calculated [9, 15, 26], such as steps or movement speed. In addition, the built-in pulse oximeter allows to calculate parameters like heart rate or burned calories. The SpiderClip sensor platform sends the data via a virtual serial communication port. The integrated script reads the serial port with the help of the *Nuget package System.IO* [9]. Default VR positional data such as position and angles can be retrieved from the attached VR tracker. The virtual watch can be downloaded from *Github* as *VR Wearable SpiderClip* [10] project. This wide range of parameters offers the possibility to use the system

[5] Nano Every (Arduino), https://docs.arduino.cc/hardware/nano-every, visited 01.03.2021

[6] MAX30101 & MAX32664 (Qwiic) (Sparkfun) https://www.sparkfun.com/products/15219, visited 01.03.2021

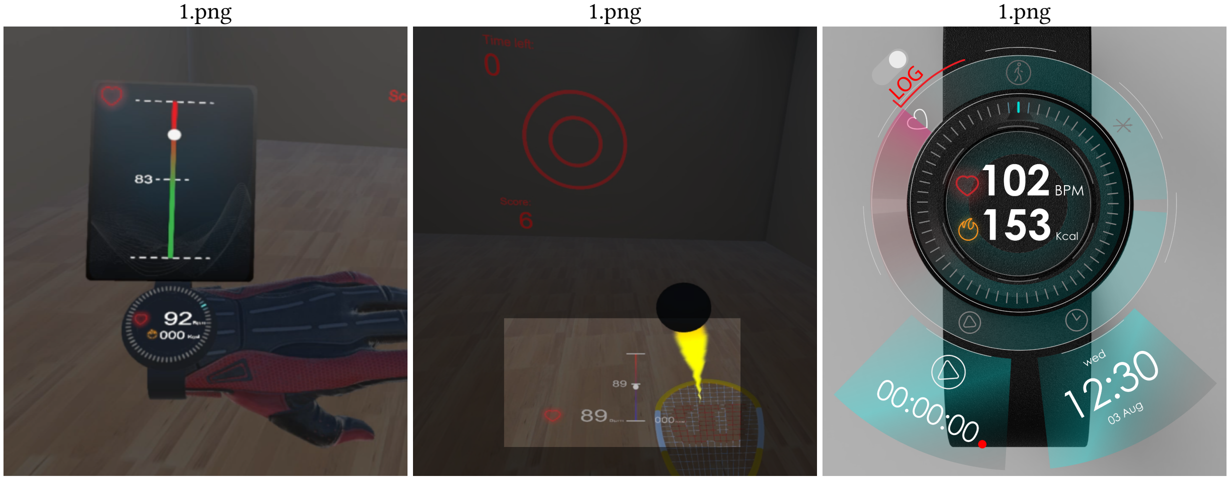
[7] HC-05 https://create.arduino.cc/projecthub/electropeak/getting-started-with-hc-05-bluetooth-module-arduino-e0ca81, visited 01.03.2021

[8] Github repository, https://github.com/D-Queck/SiderClip_Sensor.git, visited 01.03.2021

[9] System.IO (NuGet), https://www.nuget.org/packages/System.IO/, visited 01.03.2021

[10] Github repository, https://github.com/D-Queck/VR_Wearable_SpiderClip.git, visited 01.03.2021

1.png 1.png 1.png



(a) Virtual watch interface with heart rate range visualization

(b) Head-up display in VR with heart rate range visualization

(c) Virtual watch interface design with logging functionality

Figure 3: Using SpiderClip for different user interfaces

for different experiments and to collect spatial along with physiological measurements. To demonstrate and evaluate the system, we developed exemplary software components for the Unity Game Engine to present the data in different ways. For instance, a dynamic visualization of the heart rate range (cf. Figure 3a) for different exercises, a HUD-like presentation (cf. Figure 3b), and an extended virtual watch (cf. Figure 3c) that also includes low-level system controls and is intended to support researchers or developers in setting up or testing an experiment, e.g., to test different settings without removing the HMD.

5 PROOF-OF-CONCEPT STUDY

We conducted a first proof-of-concept study and user acceptance test. The goal of the study was to assess the technical reliability of the system, if users were comfortable wearing, using and moving with SpiderClip and if the VR tracking was compromised by it. In the course of the experiment, the participants wore SpiderClip while performing fitness exercises in a VR environment. The experiment took place in our lab at TU Kaiserslautern and took approximately 30 minutes per participant.

We developed a VR environment resembling a sports gym using the Unity 3D engine [25]. A virtual screen was placed in front of the user inside the VR environment to show tutorial videos of the exercises to be performed. The room was equipped with a few static props to add to a gym-like atmosphere. An HTC Vive VR system was used for this study. This included the HMD, one Vive Tracker (2018) with dongle and two base stations. To attach the tracker to the wrist, we used a hand strap for HTC Vive trackers. SpiderClip was then mounted on the tracker.

After being instructed about the nature and procedure of the experiment as well as the recording and use of their data and giving their informed consent, the participants watched a video on the screen in the virtual environment and were asked to follow the instructions. Before starting the exercise the participants were supposed to breath calmly for about 25 seconds to get an initial resting heart rate reading as reference value (Figure 4 b). Over the course of the video, four exercises (all of them different variations of squat exercises) were demonstrated. Participants were then instructed to imitate the motions as precisely as possible. To encourage usage of the wearable during the workout, the volunteers were asked to read out their heart rate as displayed on the virtual dashboard after each exercise (Figure 4 a). The live data from the wearable was logged in regular intervals, including IMU values as well as heart rate. After each exercise, participants were asked to read out their heart rate and to rate the perceived exertion based on the RPE scale of Borg [9].

After the experiment we conducted semi-structured interviews focused on wearing comfort, intuitiveness and perceived usefulness of the simulated wearable. In the interview we inquired how comfortable or uncomfortable it was for the participants to wear and move with the wearable, how easy the interface was to understand and to use and if they could imagine to use such a system in VR environments in the future. In addition to this subjective qualitative feedback, observations from the experimenter regarding the use of the system and other notable occurrences were documented in an observation protocol.

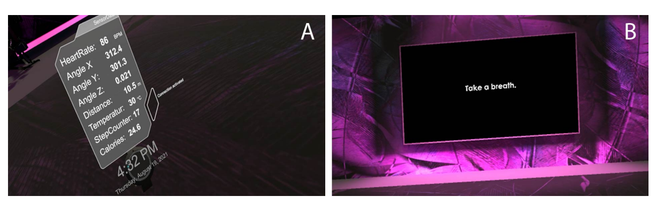


Figure 4: A shows a screenshot of the user view of the virtual wearable, B shows the screen in virtual environment

Participants. A total of 17 participants (13 self-identified as male, three as female, one preferred not to say) volunteered to participate in the experiment. Six of them were between 18 and 24 years old, ten between 25 and 34 and only one person older than 45. According to the International Physical Activity Questionnaire (IPAQ) [3] we used to assess the fitness level of the participants, the physical activity level of five participants was low, while six participants had moderate or high fitness levels, respectively. Only one person had never used a VR system before, and ten had used it only a few times in the past. Ten participants reported not using a fitness tracker in their daily lives, while only three reported using one regularly. No participant reported visual or physical problems while performing the exercises.

Results and Discussion. We calculated the overall reliability of the HR sensor over the course of all experiments by using the confidence values given by the sensor coupled with the heart rate. We decided that HR values with an associated confidence value of 0.95 or higher as sufficiently confident, while all values below that threshold were considered unreliable. That way we calculated an overall confidence over all experiments of $c = 0.825$ (i.e., 82.5% of the measured HR values were considered reliable). The median and standard deviation of the confidence values among the individual participants amount to $M = 0.872$ and $\sigma = 0.165$.

In regard to wearing comfort, seven participants stated SpiderClip was "comfortable" or that they did not notice it at all while in the virtual environment. Seven others stated they noticed it, but did not find it uncomfortable. While one participant explicitly stated wearing it over a longer period of time would not be a problem, three volunteers suggested that it might be too heavy, too uncomfortable, and "too much on the arm" for that. One person mentioned that the HR sensor on the finger was uncomfortable. Furthermore, two participants were disturbed by the cable of the VR headset and two others found the headset itself uncomfortable.

13 participants stated that the interface of the hybrid wearable was "easy", "intuitive" or "natural" to use. One person found it intuitive after a short period of practice time. Three people explicitly stated that it handled and felt "like a watch", although one of them added that it was heavier. One person claimed they did not use it much, whereas another one explicitly mentioned they consistently looked at the dashboard and two others stated they had all information they needed in the dashboard. One participant felt the dashboard disappeared too quickly when rotating the hand, another found the text in the dashboard a bit blurry.

Five participants could imagine to use such a system in the context of VR gaming. Furthermore, four people figured it could be interesting in other VR contexts like simulations or training applications. In the context of fitness applications in VR, five participants found it to be a reasonable method to exercise at home or even in the office, three noted the HR tracking would be advantageous for that while another stated they would use a smartwatch in the exactly same way when exercising normally.

Overall, the results show that SpiderClip performed well with respect to technical requirements (such as unrestricted and real-time access to data) and data measurement, which is of course limited by measurement accuracy of the integrated components. In terms of usability and ergonomics, subjective feedback suggests that for the majority of participants, the device was easy to use and did not significantly increase physical strain. However, unsurprisingly, the current generation of VR HMDs in general still leaves lots of room for improvement in this regard.

6 CONCLUSION AND FUTURE WORK

In this work, we presented SpiderClip, a collection of open-source hardware and software components which lower the threshold to experiment with wearable technology in VR. In contrast to commercial smartwatches and fitness trackers, SpiderClip provides unrestricted real-time access to all measurements. The presented example setup includes common sensors like an IMU, and a heart rate sensor, which provide the foundation for many application scenarios.

We conducted a first proof-of-concept user study with 17 participants. Our results show that SpiderClip can be successfully used within the context of a VR exercising application. In our lab, SpiderClip provides the foundation for ongoing larger studies of different aspects of VR exergame design and effects. We are constantly working on extending and improving SpiderClip, e.g., by supporting various VR hardware, adding additional sensors and extending the software part to provide different ways of presenting the data inside VR applications.

ACKNOWLEDGMENTS

This work was partially supported by the German Research Foundation (DFG) within the priority program "Scalable Interaction Paradigms for Pervasive Computing Environments" (SPP2199), by the Klaus Tschira Foundation within the graduate school "Empowering Digital Media" at the University of Bremen, and by the Research Initiative of Rhineland-Palatinate within the priority area "AI Enhanced Cognition and Learning" and the graduate program "Cognitive Dynamics" both at TU Kaiserslautern.

REFERENCES

[1] Aslihan Tece Bayrak, Rahul Kumar, Jak Tan, DeVon AhMu, Jordan Hohepa, Lindsay A. Shaw, Christof Lutteroth, and Burkhard C. Wünsche. 2017. Balancing Different Fitness Levels in Competitive Exergames Based on Heart Rate and Performance. In *Proceedings of the 29th Australian Conference on Computer-Human Interaction* (Brisbane, Queensland, Australia) *(OZCHI '17)*. Association for Computing Machinery, New York, NY, USA, 210–217. https://doi.org/10.1145/3152771.3152794

[2] Peter Blank, Julian Hossbach, Dominik Schuldhaus, and Bjoern Eskofier. 2015. Sensor-based stroke detection and stroke type classification in table tennis. 93–100. https://doi.org/10.1145/2802083.2802087

[3] Cora L Craig, Alison L Marshall, Michael Sjöström, Adrian E Bauman, Michael L Booth, Barbara E Ainsworth, Michael Pratt, ULF Ekelund, Agneta Yngve, James F Sallis, et al. 2003. International physical activity questionnaire: 12-country reliability and validity. *Medicine & science in sports & exercise* 35, 8 (2003), 1381–1395.

[4] Hendrik Engelbrecht, Robert W Lindeman, and Simon Hoermann. 2019. A SWOT analysis of the field of virtual reality for firefighter training. *Frontiers in Robotics and AI* 6 (2019), 101.

[5] Juan Haladjian, Zardosht Hodaie, Han Xu, Mertcan Yigin, Bernd Bruegge, Markus Fink, and Juergen Hoeher. 2015. KneeHapp: A Bandage for Rehabilitation of Knee Injuries. In *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers* (Osaka, Japan) *(UbiComp/ISWC'15 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 181–184. https://doi.org/10.1145/2800835.2800909

[6] Teresa Hirzle, Jan Rixen, Jan Gugenheimer, and Enrico Rukzio. 2018. Watchvr: Exploring the usage of a smartwatch for interaction in mobile virtual reality. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–6.

[7] Samory Houzangbe, Olivier Christmann, Geoffrey Gorisse, and Simon Richir. 2018. Integrability and reliability of smart wearables in virtual reality experiences: a subjective review. In *Proceedings of the Virtual Reality International Conference-Laval Virtual*. 1–6.

[8] Pradthana Jarusriboonchai and Jonna Häkkilä. 2019. Customisable wearables: exploring the design space of wearable technology. In *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*. 1–9.

[9] Sampath Jayalath, Nimsiri Abhayasinghe, and Iain Murray. 2013. A gyroscope based accurate pedometer algorithm. In *International Conference on Indoor Positioning and Indoor Navigation*, Vol. 28. 31st.

[10] Mallory Ketcheson, Zi Ye, and T.C. Nicholas Graham. 2015. Designing for Exertion: How Heart-Rate Power-Ups Increase Physical Activity in Exergames. In *Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play* (London, United Kingdom) *(CHI PLAY '15)*. Association for Computing Machinery, New York, NY, USA, 79–89. https://doi.org/10.1145/2793107.2793122

[11] Tanja Kojić, Lan Thao Nugyen, and Jan-Niklas Voigt-Antons. 2019. Impact of Constant Visual Biofeedback on User Experience in Virtual Reality Exergames. In *2019 IEEE International Symposium on Multimedia (ISM)*. 307–3073. https://doi.org/10.1109/ISM46123.2019.00068

[12] Wanwan Li, Biao Xie, Yongqi Zhang, Walter Meiss, Haikun Huang, and Lap-Fai Yu. 2020. Exertion-aware path generation. *ACM Transactions on Graphics (TOG)* 39, 4 (2020), 115–1.

[13] Manuel Meier, Paul Streli, Andreas Rene Fender, and Christian Holz. 2021. Demonstrating TapID for Rapid Touch Interaction on Surfaces in Virtual Reality for Productivity Scenarios. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–4.

[14] Paul Milgram and Fumio Kishino. 1994. A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems* 77, 12 (1994), 1321–1329.

[15] Bogdan Muset and Simina Emerich. 2012. Distance measuring using accelerometer and gyroscope sensors. *Carpathian Journal of Electronic and Computer Engineering* 5 (2012), 83.

[16] Matthias Oberhauser, Daniel Dreyer, Reinhard Braunstingl, and Ioana Koglbauer. 2018. What's Real About Virtual Reality Flight Simulation? *Aviation Psychology and Applied Human Factors* (2018).

[17] Krzysztof Pietroszek and Daniel Kharlamov. 2016. TickTockRay: Smartwatch Raycasting for Mobile HMDs. In *Proceedings of the 2016 Symposium on Spatial User Interaction*. 181–181.

[18] Krzysztof Pietroszek, Liudmila Tahai, James R Wallace, and Edward Lank. 2017. Watchcasting: Freehand 3D interaction with off-the-shelf smartwatch. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, 172–175.

[19] Franca Alexandra Rupprecht, Achim Ebert, Andreas Schneider, and Bernd Hamann. 2017. Virtual reality meets smartwatch: Intuitive, natural, and multimodal interaction. In *Proceedings of the 2017 chi conference extended abstracts on human factors in computing systems*. 2884–2890.

[20] Heidi Similä, Milla Immonen, and Timo Niemirepo. 2018. Mobile fall risk assessment solution for daily-life settings. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 1530–1533.

[21] Jeff Sinclair, Philip Hingston, and Martin Masek. 2009. Exergame Development Using the Dual Flow Model. In *Proceedings of the Sixth Australasian Conference on Interactive Entertainment* (Sydney, Australia) *(IE '09)*. Association for Computing Machinery, New York, NY, USA, Article 11, 7 pages. https://doi.org/10.1145/1746050.1746061

[22] Gaganpreet Singh, William Delamare, and Pourang Irani. 2018. D-SWIME: A design space for smartwatch interaction techniques supporting mobility and encumbrance. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–13.

[23] Sharon Stansfield, Daniel Shawver, Annette Sobel, Monica Prasad, and Lydia Tapia. 2000. Design and implementation of a virtual reality system and its application to training medical first responders. *Presence: Teleoperators & Virtual Environments* 9, 6 (2000), 524–556.

[24] Carolin Stellmacher, Nadine Wagener, and Kuba Maruszczyk. 2021. Enhancing VR Experiences with Smartwatch Data. (2021).

[25] Unity Technologies [n.d.]. *Unity engine*. Unity Technologies. https://unity.com/

[26] R Williamson and BJ Andrews. 2001. Detecting absolute human knee angle and angular velocity using accelerometers and rate gyroscopes. *Medical and Biological Engineering and Computing* 39, 3 (2001), 294–302.

[27] Biao Xie, Yongqi Zhang, Haikun Huang, Elisa Ogawa, Tongjian You, and Lap-Fai Yu. 2018. Exercise Intensity-Driven Level Design. *IEEE Transactions on Visualization and Computer Graphics* 24, 4 (2018), 1661–1670. https://doi.org/10.1109/TVCG.2018.2793618

[28] Christina Zehnter, Alexander Burger, and Jivka Ovtcharova. 2012. *Key-Performance-Analyse von Methoden des Anforderungsmanagements*. Vol. 7620. KIT Scientific Publishing. 31–32 pages.